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A Swing-Arm On-Machine Inspection Method for Profile Measurement of Large Optical Surface in Lapping Process

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Generally, the optical components are fabricated by grinding, lapping, and polishing. And, those processes take long time to obtain such a high surface quality. Therefore, in the case of large optical component, the on-machine inspection (OMI) is essential. Because, the work piece is fragile and difficult to set up for fabricating and measuring. This paper is concerned about a swing-arm method for measuring surface profile of large optical concave mirror. The measuring accuracy and uncertainty for suggested method are studied. The experimental results show that this method is useful specially in lapping process with the accuracy of 3~5 μm. Those inspection data are provided for correcting the residual figuring error in lapping or polishing processes.

Key Words: Aspherical optics, Coordinate Measuring Machine (CMM), Lapping, LVDT (Linear Variable Differential Transformer), On-Machine Inspection (OMI), Profile measurement, Swing-Arm

Nomenclature

H_b, H, L : Swing arm geometric dimensions
M, N : LVDT set-up geometric dimensions
α : Rotating angle of swing-arm
θ, ϕ : Tilting and rolling angle of swing-arm
$^{A}\mathbf{P}$: Vector in coordinate {A}
$^{A}\mathbf{P}_{BORG}$: Vector indicating the origin of {B} in coordinate {A}
$^{A}_{B}R$: Rotational matrix of coordinate {A} to the coordinate {B}
{A} : Reference coordinate
{B}, {C}, {D} : Local coordinates

1. Introduction

Nowadays, one of typical Nano machining technologies could be the optical component manufacturing, because its form accuracy needs at least less then 0.1 μm, up to few nanometer. The industrial requirement of the optics becomes more precise using aspherical lens which makes optical system compact and smaller than spherical one. The aspherical optics are so difficult to figure and inspect that the product is expensive. The general fabrication process of large optics, which is using in photo lithographing system (stepper) or astronomical purpose, is as shown in Fig. 1. Between the processes, on-machine inspection (OMI) is necessary to cover the difficulty to handle such a large and breakable work piece. Also, the OMI is effective to reduce the set-up time in case of repetitive or corrective lapping or polishing. The profile measuring data is necessary for the next stage to determine the depth of lapping or polishing. For surface profile measurement of optical component, interferometry is usual and shows high precision accuracy. However, the method requires a very fine surface object and a strict anti-vibration environment. Particularly, for measuring the aspherical profile, a null lens, which is a master piece and expensive to fabricate, is neces-

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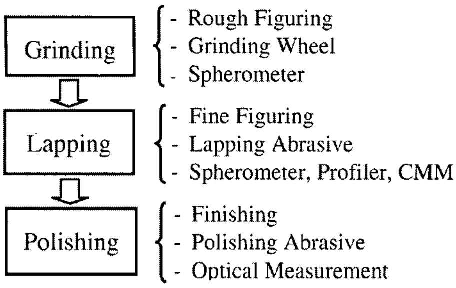


Fig. 1 General fabricating process of large optical component

sary (Yang and Walker, 2001 ; Martin et al., 2002). The swing-arm method for measuring large optics had been introduced rarely (Burge, 1996). Recently, the accuracy of contacting transducer using LVDT is greatly improved up to 0.01 μm. There are two types of profile measuring method using the contacting probe with mechanical linkage, one 'plunge' and the other 'pivot' method (Walker et al., 2003). The 'plunge' method requires at least two axes of moving system. But on the other hand 'pivot' method only one pivot is used for tracing on a particular surface. It is obvious that the more axis of movement includes the more uncertainty of geometric measuring error.

In this study, using the precision LDVT transducer, a swing arm profile on-machine measuring system is investigated. The swing arm method is useful for measuring spherical surface because the measuring range of LVDT can be minimized and it reduces the uncertainty of sensor relatively. About the overall measuring accuracy due to misalignment and geometry of the swing arm system, are also described.

2. Design of Swing-arm On-machine Measuring System

Fig. 2 shows a typical optical lens fabrication system for lapping or polishing. The polishing tool moves repeatedly in an arc path on the work piece with rotating table. The position and sweeping range of the polishing tool can be controlled by a numerical controller (NC). The removal rate of the work piece is proportional to the

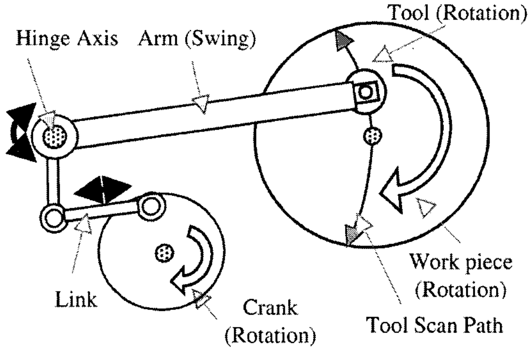


Fig. 2 A typical lapping or polishing machine for optical lens

sweeping number on a particular area which is to be removed for profiling.

We designed an on-machine swing arm measuring device for lapping process of large concave mirror. The linkage system is similar with the lapping machining mechanism as shown in Fig. 3. A LVDT probe is fixed at the end of linkage and the probe moves along a spherical arc path. The deviation with the spherical arc and the manufactured surface profile will be shown as the LVDT signal. Different arc paths are measured with indexing of the work piece table across the center of rotating axis. The axis of tool is tilted with angle θ and the probe tip is contacted at a point P in the normal direction with respect to the spherical concave surface. The advantage of this system is that the probe is always contacting in the normal direction with the spherical surface, which removes the cosine error for probing device. If the

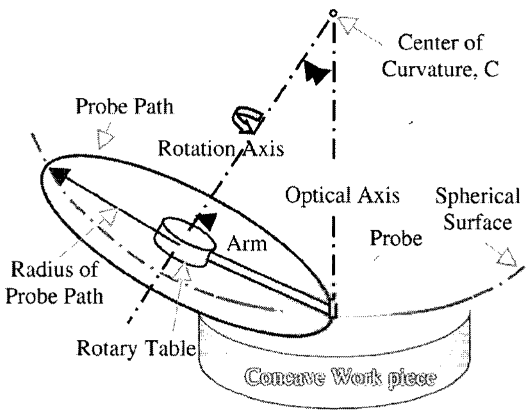
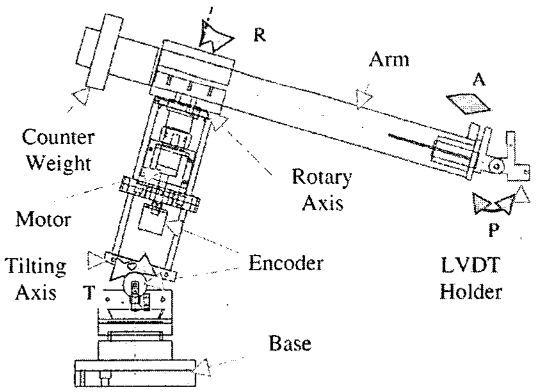


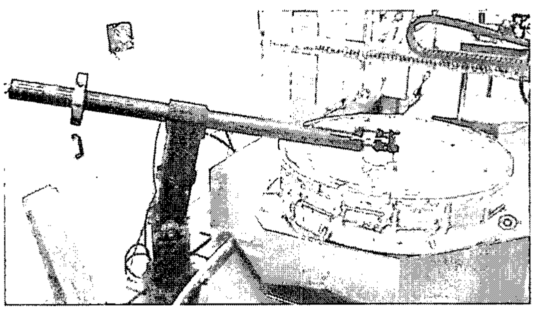
Fig. 3 Swig-arm profile measuring mechanism

manufactured surface has no profile error for designed one, the probing signal will be shown as 'zero' along the spherical path. In the case of aspherical surface, the probing signal will be shown as continuously increasing or decreasing from the center point C. Thus, the aspherical constant can be calculated from the deviation value with respect to the spherical surface.

A swing arm measuring machine is designed and manufactured for inspecting a concave mirror as shown in Fig. 4. The column and work piece table are fixed strongly in one body on a heavy steel table, which is important to prevent the relative deflection between probe and measuring surface. The working table moves for inspection (on machine measurement) during or after lapping process. The column has two axes of rotating (R) and tilting (T). LVDT holder is able to move in linear (A) and tilting (T) axis for positioning in normal direction with the measuring surface. The column is rotated using a stepping motor with timing belt to position a certain point on the measuring surface. A counter weight is used to remove excessive pressure at the LVDT in the opposite direction of the arm.



(a)



(b)

Fig. 4 Design of swing-arm measuring system and set up on the side of a lapping machine for concave mirror

3. Geometric Error Analysis of Swing-Arm Measuring System

A geometric error model for the swing-arm measuring system is suggested using a homogeneous coordinate transformation between axes as Fig. 5. The dominant axes of this system will be the X, Z in the arm and the LVDT reading direction, respectively. However, the column and arm may be tilted in the Y direction too, for the set-up (installment) procedure of the machine. The position vector, $^{B}\mathbf{P}$ in the local coordinate {B} is calculated with respect to the reference coordinate {A} using the rotation and translation coordinate transformation. The variation in the Z axis at probe position 'P' can be calculated along the radial angular position 'α' of the swing arm. Geometric error of the swing arm and column results in signal value of the LVDT reading. The reading value can be calculated using the coordinate transformation for certain misalignment of the swing arm. Two kind of geometric errors due to misalignment or non rigid frame of the system are existed, which are rolling of the arm and tilting of the column.For the swing arm linkage system as shown in Fig. 6, the coordinate transformation vector is expressed as Eq. (1). Thus, the coordinate of LVDT contacting point 'P' is

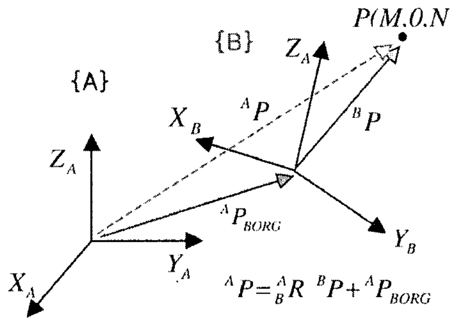


Fig. 5 Coordinate transformation between two systems {A} and {B}

calculated as Eq. (2), for rolling angle ϕ and tilting angle θ along the swing angle α.

$$^{A}P={}^{A}_{B}R\,{}^{B}P+{}^{B}_{C}R\,{}^{D}P+{}^{A}P_{DORG} \tag{1}$$

$$\begin{aligned} P_X&=F_1(\theta)\cdot\cos(\alpha)+F_2(\theta)\\ P_Y&=F_3(\theta,\phi)\cdot\sin(\alpha)+F_4(\theta,\phi)\cdot\cos(\alpha)+F_5(\theta,\phi)\\ P_Z&=F_6(\theta,\phi)\cdot\sin(\alpha)+F_7(\theta,\phi)\cdot\cos(\alpha)+F_8(\theta,\phi)\end{aligned} \tag{2}$$

where $F_{1\text{-}8}$ are geometric constants and trigonometric functions of designed swing arm linkage, H_b, H and L as follows;

$$\begin{aligned} F_1&=M\cdot c^2(\theta)-s(\theta)\cdot c(\theta)+L\cdot c(\theta)\\ F_2&=-M\cdot s^2(\theta)+N\cdot s(\theta)\cdot c(\theta)+H\cdot s(\theta)\\ F_3&=L\cdot c(\phi)-N\cdot s(\theta)\cdot c(\phi)\\ F_4&=M\cdot c(\theta)\cdot c(\phi)+M\cdot s(\theta)\cdot c(\theta)\cdot s(\phi)\\ &\quad-N\cdot s^2(\theta)\cdot s(\phi)+L\cdot s(\theta)\cdot s(\phi)\\ F_5&=-M\cdot s(\theta)\cdot c(\theta)\cdot s(\theta)\\ &\quad-N\cdot c^2(\theta)\cdot s(\phi)-H\cdot c(\theta)\cdot s(\phi)\\ F_6&=L\cdot s(\phi)-N\cdot s(\theta)\cdot s(\phi)\\ F_7&=M\cdot c(\theta)\cdot s(\phi)-M\cdot s(\theta)\cdot c(\theta)\cdot c(\phi)\\ &\quad+N\cdot s^2(\theta)\cdot c(\phi)-L\cdot s(\theta)\cdot c(\phi)\\ F_8&=M\cdot s(\theta)\cdot c(\theta)\cdot c(\phi)+N\cdot c^2(\theta)\cdot c(\phi)\\ &\quad+H\cdot c(\theta)\cdot c(\phi)+H_b\end{aligned} \tag{3}$$

where c=cos, s=sin, M and N are the X, Z coordinate at the LVDT contacting point as shown in Fig. 5. Fig. 7(a) is the simulation result of LVDT reading value (error) for a given rolling error of the arm using the geometric error model. The reading error is calculated using Eq. (2) in the Z direction for swing diameter 640 mm and geometric dimensions of the designed swing arm measuring system. The influence of rolling angle (±0.5°) in LVDT direction appears like a line such a large size of concave mirror (radius

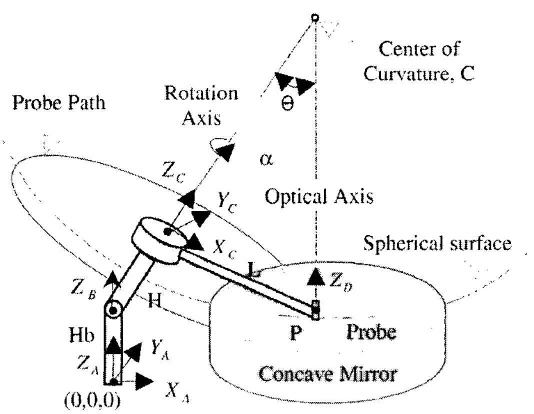


Fig. 6 Axis definition of the swing arm measuring machine for geometric error modeling

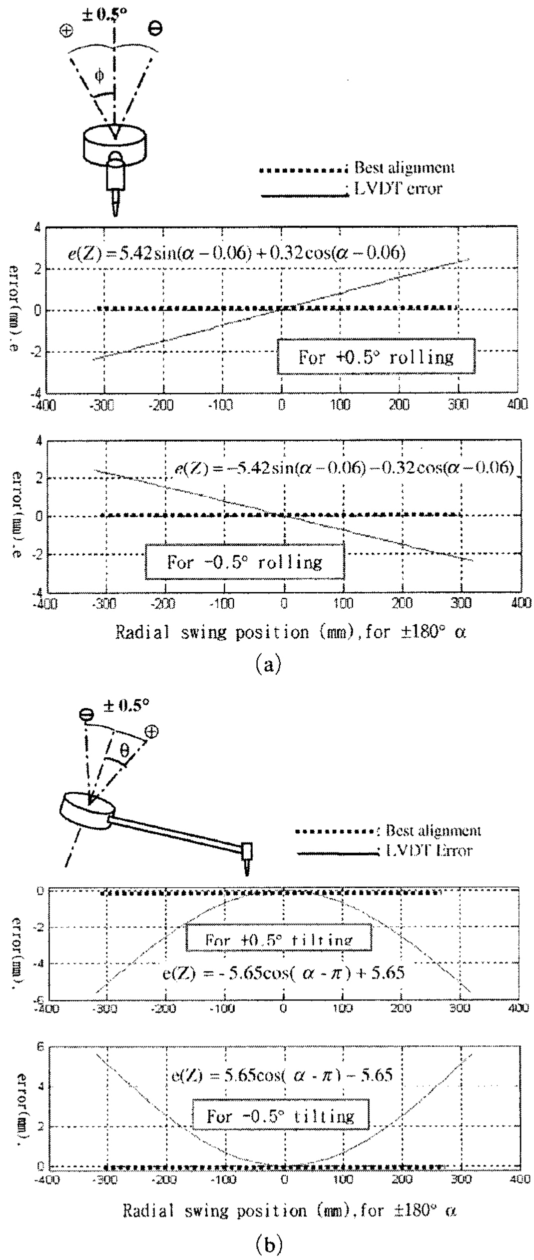


Fig. 7 Simulation of LVDT reading value (error) in the Z direction for a given geometric error of the arm for 640 mm swing diameter

3,000 mm). Thus, in this study the rolling angle is calculated approximately as an arc tangent of the first order constant of a line or a polynomial fitting for measured profile data.

As the similar way, for a tilting angle (±0.5°), the LVDT error is assumed along the radial swing path (for ±180° α) on the concave mirror as shown in Fig. 7(b). It shows that the influence of tilting angle is symmetrical with respect to the center of concave mirror, rotating axis. The geometric constants in Eq. (2), $P_z(F_{6-8})$, can be calculated using curve fitting of the measured LVDT reading. The reading error is minimized using mechanical adjustment for installation procedure of the swing arm machine.

4. Swing-Arm Experiment and Verification

For measuring the surface profile of a concave mirror, 640 mm diameter, we used a LVDT (0.5 μm resolution) with ±2.5 mm measuring range which should be covered the profile error after machining (grinding or lapping). Usually, general machining center with diamond tool is used for grinding such a large optics and the surface profile accuracy is less than ±1 mm. Fig. 8 shows the measured profile error of the concave mirror (ϕ640 mm) during the lapping process. It is appeared that rolling influence is dominant in our swing arm machine, compared the simulation results in Fig. 7. As mentioned in section 3, the vector Pz in LVDT measuring direction is assumed as a polynomial curve approximately. Thus, the roll error is calculated as 0.026° in (+) direction as the tangent of the first order term from the polynomial equation of the measured data. It is shown that the tilting effect, which is symmetrical with respect to the axis of concave surface, is very small compared to the rolling one relatively. Tilting angle is calculated by the curve fitting of Eq. (2) after removal of the rolling angle as shown in Fig. 9.

Final measured profile error is shown in Fig. 10 after removal of the rolling and tilting error of the swing-arm device designed in this study. The data include a surface profile error of the concave

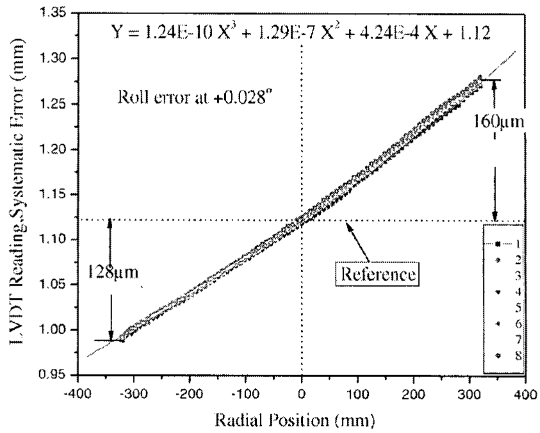


Fig. 8 Measured surface profile error for a lapped concave mirror (ϕ640 mm, curvature 3,000 mm) and calculation of rolling angle (eight times repeat measurement)

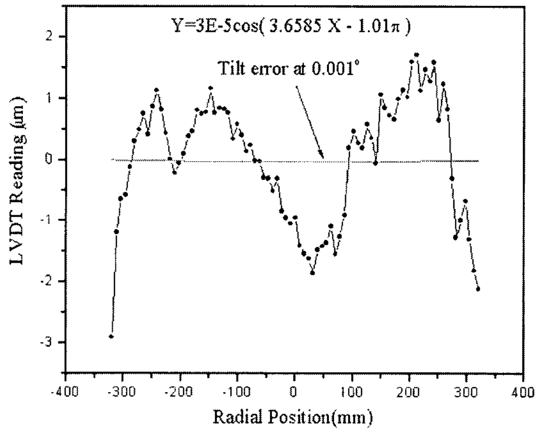


Fig. 9 Calculation of tilting angle after removal of the rolling angle

mirror and an error of the measuring device itself. The surface profile was measured using a modified Shack-Hartmann method which is an optical test with an accuracy of ±0.05 μm for large optical reflector (Daniel Malacara-Hernandez and Daniel Malacara-Doblado, 1999). The surface profile error of the concave mirror was approximately 0.9 μm P-V. Therefore, it is shown that the accuracy of the swing-arm measuring device could be maximum 4.9 μm for ϕ640 mm and curvature 3,000 mm concave mirror. The accuracy will be influenced by such as, run-out error of the rotating spindle, swing angle error

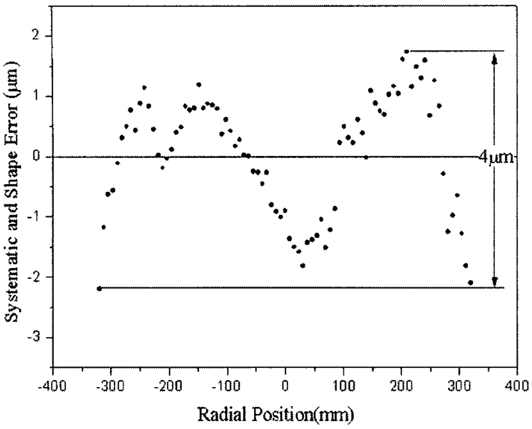


Fig. 10 Final surface profile error for the concave mirror (ϕ640 mm) after removal of rolling and tilting angle of the swing-arm machine

of the indexing system, deflection of the arm, uncertainty of the Shack-Hartmann method and LVDT, and so on.

5. Conclusions

It is shown that the swing-arm measuring method can be used as an on-machine measuring device for large optics lapping or polishing machine with an accuracy of less than 5 μm. This method is useful as an inspection system between lapping and polishing process of large optical components without transferring the work piece to other measuring room. The measured profile data is necessary for corrective lapping process and ultimately it makes to reduce the lapping time. The swing-arm is an economical measuring device compared to the other optical method, such as interferometry. The set-up errors, rolling and tilting angle, of the swng-arm can be simulated and removed from the measured surface profile data. It is expected that the measuring accuracy will be improved using high rigid air bearing in the rotating spindle and non-contact type gap sensor suitable for optical material. This method also will be used to measure large aspherical optical concave or convex mirrors.

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